Voyager Mission, Detailed processing of weak magnetic fields; II - Update on the cleaning of Voyager magnetic field density **B** with MAGCALs

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Summary: first are presented a few central guiding principles used in the cleaning of the magnetic field density **B** signal. Here we describe the aims of this paper related to the task:

a) Visitation of the method of using the two magnetometers per platform (Voyager 1, and Voyage2).

b) discussion of example of component in the radial direction from the Sun, i.e., B_z PL (=payload)

c) illustration of (i) calibration, and (ii) signal reversal parts of the MAGCALs sequence for **B** (PL)

d) an interpretation on the meaning of the MAGCALs signal reversal element

e) information gain on the plasma **B**: (i) from the reversal element of MAGCALs, and (ii) with assumed constraints on |**B**|.

Essentially the work performed here is focused in generating the zero-reference level to the raw-data (observations).

[Although not the purpose of this document, it may benefit the interested reader to know that once a satisfactory result is achieved, a table of zeroes to the magnetic flux density field is given to production. The 48s averages of the production data are delivered to a senior team member [Burlaga, (2005-2015)] who edits the data and prepares hour averages of the data. He delivers the edited 48s and hour averages to the NASA's Space Physics Data Facility (SPDF), which is a project of the Heliospheric Science Division (HSD) at NASA's Goddard Space Flight Center. The data are made available to the public by the SPDF.]

1. Revisiting the method of using the two magnetometers per platform (Voyager 1, and Voyage2).

The calibration of this **B-**signal (i.e the so defined *magnetic flux [or field] density, see e.g., Jackson,1962, Hayt, 1981)* external to the magnetic field density of the SC is the purpose of the task we address in this supplement attempting to further our calibration work using the periodic (every 29 days) calibration steps described under the acronym MAGCAL, see Berdichevsky, 2009.

When we look forward to extend/update Berdichevsky, 2009 in our current processing of the identification of the **B** in VOYAGER it is worth emphasizing that it is done following the guidance by Acuña, 2005 – 2008, and Burlaga, 2009 – 2015. Henceforth, the technique used is the careful study of the reproduction of the observations by both magnetometers in the SC. In that sense the developed approach includes the use of MAGROLs and the guidance from:

A) When changes in the signal time sequence repeats exactly in form and counts both in the inboard and in the outboard magnetometers we interpret that we are observing with the instrument the behavior of the magnetic field density that permeates the plasma and not any variation in the field itself of the SC.

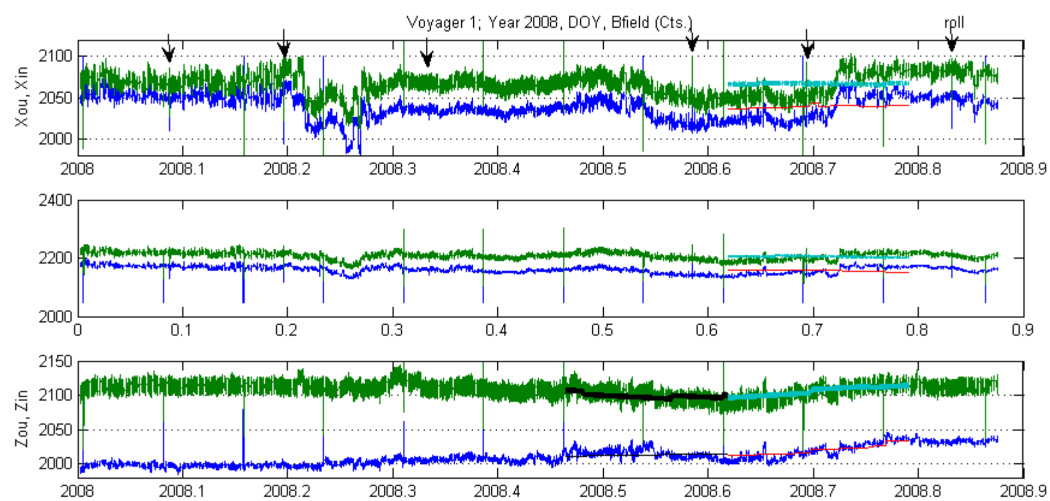
B) When changes are observed in the **B**-field in only one of the two magnetometers in the SC it is accepted that as correct observations from the magnetometer showing no change.

C) When changes in the magnetometers are different with respect to the same component intensity, e.g., in out-board magnetometer the component value increases while in the in-board magnetometer same component intensity decreases we understand that further work is needed to identify the direction in change of the actual **B**-signal.

2. discussion of example of component in the radial direction from the Sun, i.e., B_z PL (=payload)

We follow the previously reintroduced technique (Section 1) to identify when it is likely that the radial field from the Sun measured in the spacecraft departs on average from our constrain for the radial direction from the Sun (approximately Z coordinate in PL system) for B_{zPL} to be on average zero. We also identify when the spacecraft find themselves in the Sheath resulting from the termination shock and as observed with VOYAGER 1 extending from the Solar Wind supersonic region ending now in the local

Figure 1. *In top panel each arrow indicates location in time of a MAGROL, at which B_{zPL} on average is set equal 0.*

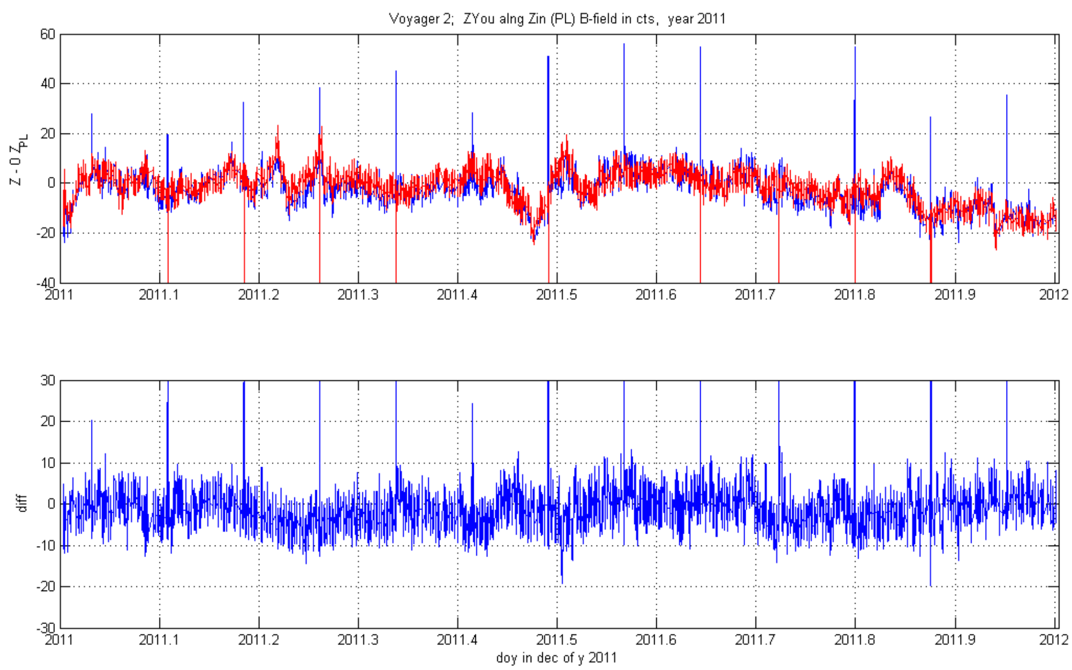


interstellar medium, Stone, 2013. Figure 1 illustrates in the case of VOYAGER 1 the simultaneous, coherent change in inboard and outboard Z-raw data following MAGROL near time 2008.7 of the magnetic field density component along Z-PL. The Figure 1 shows the start near time 2008.7 of a gradual positive change in inboard and outboard Z PL intensity, which at the end we estimated to be +20 Cts.

This change is respectfully interpreted by us as a actual effect coming from the plasma magnetic field of the medium in which Voyager 1 is immersed and constitute a guidance in all posterior evaluation of the Z PL component of the magnetic field extending up to the present (year 2015) in the determination of the intensity and orientation of the observed magnetic field, currently in the region which appears to be different in nature from anything else so far encountered before in the realm of the magnetized plasma with origin at the Sun

.In the case of Voyager 2 we identify a consistent deviation in inboard and outboard magnetic field intensity Bz PL at the end of the year 2011 as can be observed in the cleaned data for both magnetometers in this SC in the Figure 2.

Figure 2: Calibrated Z-PL component shows shift, at time ~2011.87, to negative values in both sensors



Notice that the deviation for Z PL from the Parker adjustment to zero made regularly at each MAGROL location is the opposite that the one observed in Figure 1, bottom panel (Voyager 1).

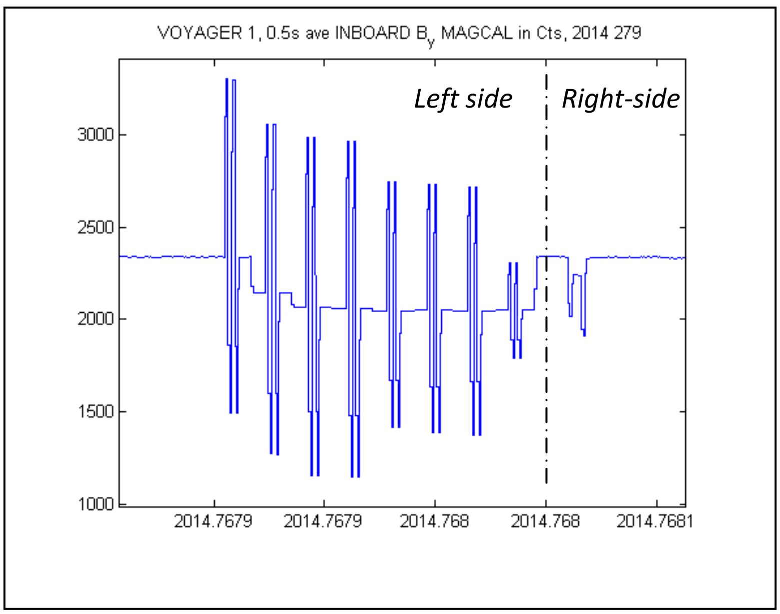
The condition that allows the estimate of the intensity of the magnetic field density along Z PL is further monitored with the help of the MAGCALs, recently described in Berdichevsky, 2009, in the absence of a direct periodic determination of the intensity that so well allows us to find the zero calibration of its value with the roll of the SC around the Z PL axis that is also the direction of an imaginary line connecting Earth to any one of the SC and very close already for a long time to a radial direction from the Sun.

3. I*ll*ustration of (i) calibration, and (ii) signal reversal parts of the MAGCALs sequence for B (PL)

For every resolution sensitivity of the electronic calibration (MAGCAL) of **B** the 1st step is to go through the identification of the zero level, which is obtained up to displacement of its actual value by the intensity and direction of the **B**-field component present at the sensor at the time of the calibration. The lower the sensitivity the lesser the zero value for **B** is affected by the presence of the **B** along the PL direction of the particular sensor considered.

The field structure to the left illustrates from the highest to the lowest sensitivity step level of the instrument as a function of time (this is from left to right). Of particular interest for us is the 2nd part, which corresponds to the determination using a flip in the sign of the signal in the 5 step process we can see indicated on the right of the Figure 3.

Figure 3



The feature of interest to us is the one on the right of Figure 3. The whole signal, in this case along the direction Y_{PL} has the true sign at the start and end of the feature, and the opposite sign exactly in the middle. This way we know that the half-value is the zero of the magnetic field density component B_y in the PL coordinate system. I.e., in counts the zero for the signal along Y_{PL} is at ~ 0.5 (2336 + 2243) Cts

Symplifying the calibration to the nominal highest sensitive resolution of the magnetomenter at ~ 0.005 nT/Ct, we conclude that on DOY 279, year 2014 the value

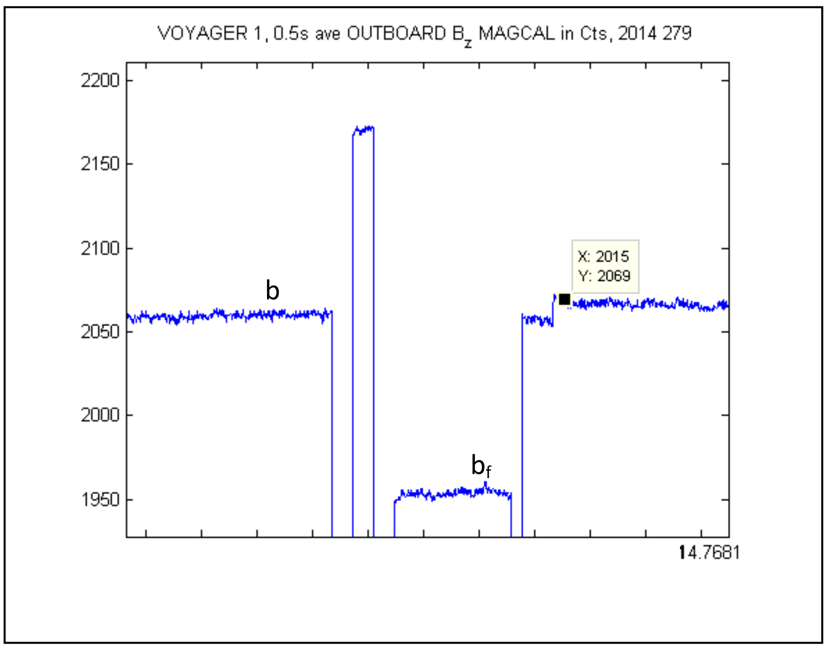
$$B_{yT} \cong [2336 - 0.5\,(2336 + 2243)] \text{ Cts } 0.005 \text{ nT/Ct} = 0.2325 \text{ nT}$$

combines the external field we are interested in evaluating with the internal field generated by the SC at the internal magnetometer. To emphasize that the evaluation using MAGCALS gives the total component of the magnetic field density is shown by adding the T in the label of the observed field component, i.e., we write B_{yT}. The main topic of discussion that follows from this work is how we do extract along the Z PL direction the medium's value of that magnetic field component considering that we do not have available the MAGROLs for its determination.

4. Extracting the meaning of the signal gain from the MAGCALs signal reversal element

When extracting the value of the absolute Zero of a **B**-field component we evaluate carefully several values after the detector determines the component in its regular set-up 'b', which corresponds to its actual sign. Next we do the evaluation when the sensor is operating in a reversed mode 'b_f' as we can see with the help of Figure 4.

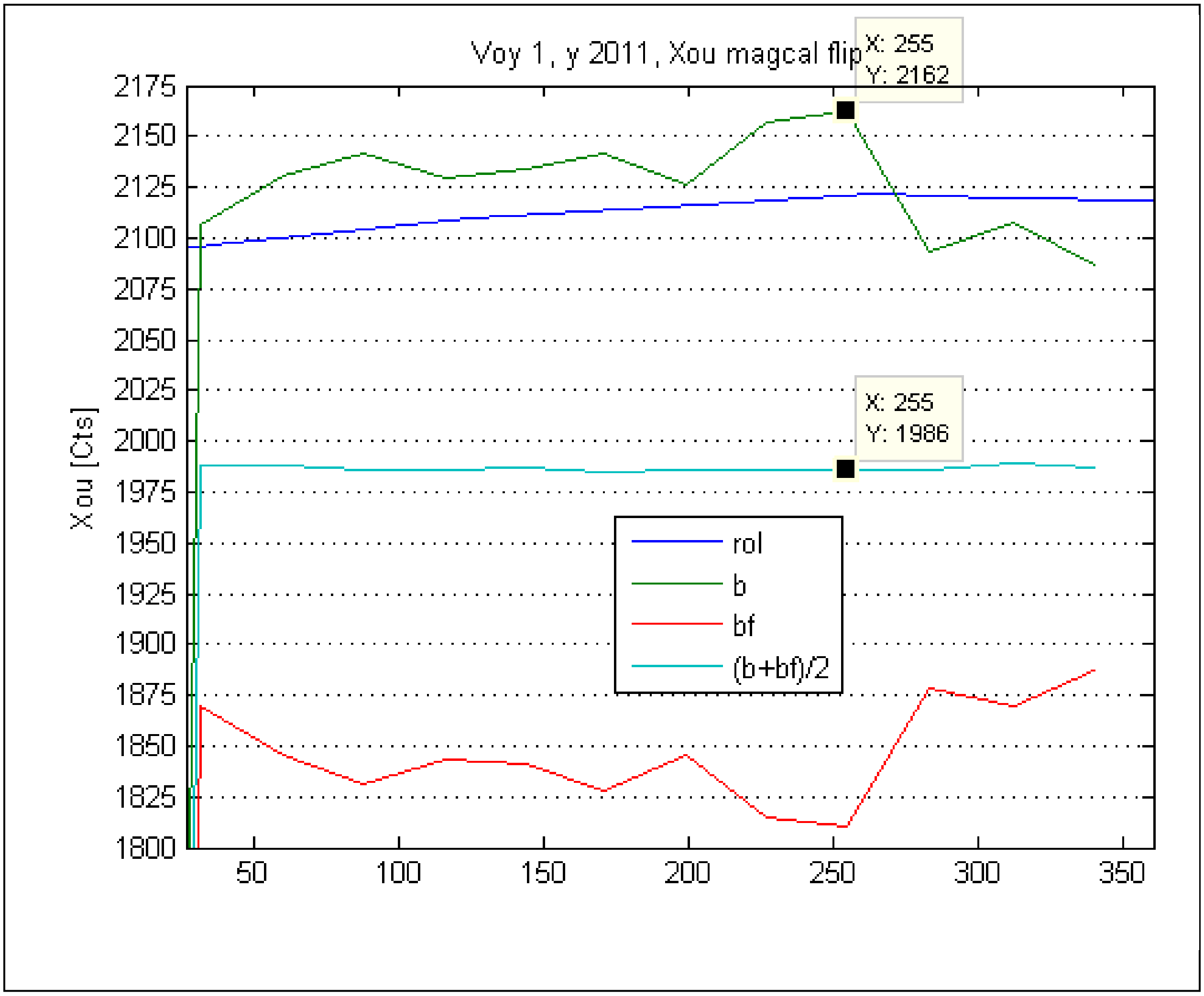
Figure 4



First notice that the vectors used in this analysis are at the highest time resolution of the instrument of one vector every ~ 1 second. Next for each value obtained from a careful averaging of the observation, its value is entered in a table that allows us to learn about the long term evolution of the total component of the **B**-field obtained with the MAGCALs, i.e., every 29 days. In this way the created table contains values as indicated on the plot of Figure 5

The Figure 5 illustrates with the blue line the location of the zero of the medium's magnetic field, i.e, the **B-**field we are interested in measuring. Consequently, the magnetized plasma B_x PL magnetic field is the

Figure 5: MAGROL's dark-blue-line is the zero-line of the medium. Light-blue-line gives MAGCAL's zero.



difference between the MAGCALs green-line labeled 'b' and the MAGROLs blue-line labeled 'rol'. On the other hand the MAGCALs combination of the SC and plasma magnetic field density B_{xT} is the difference between the green-line labeled 'b' and the light blue-line labeled '(b+bf)/2'.

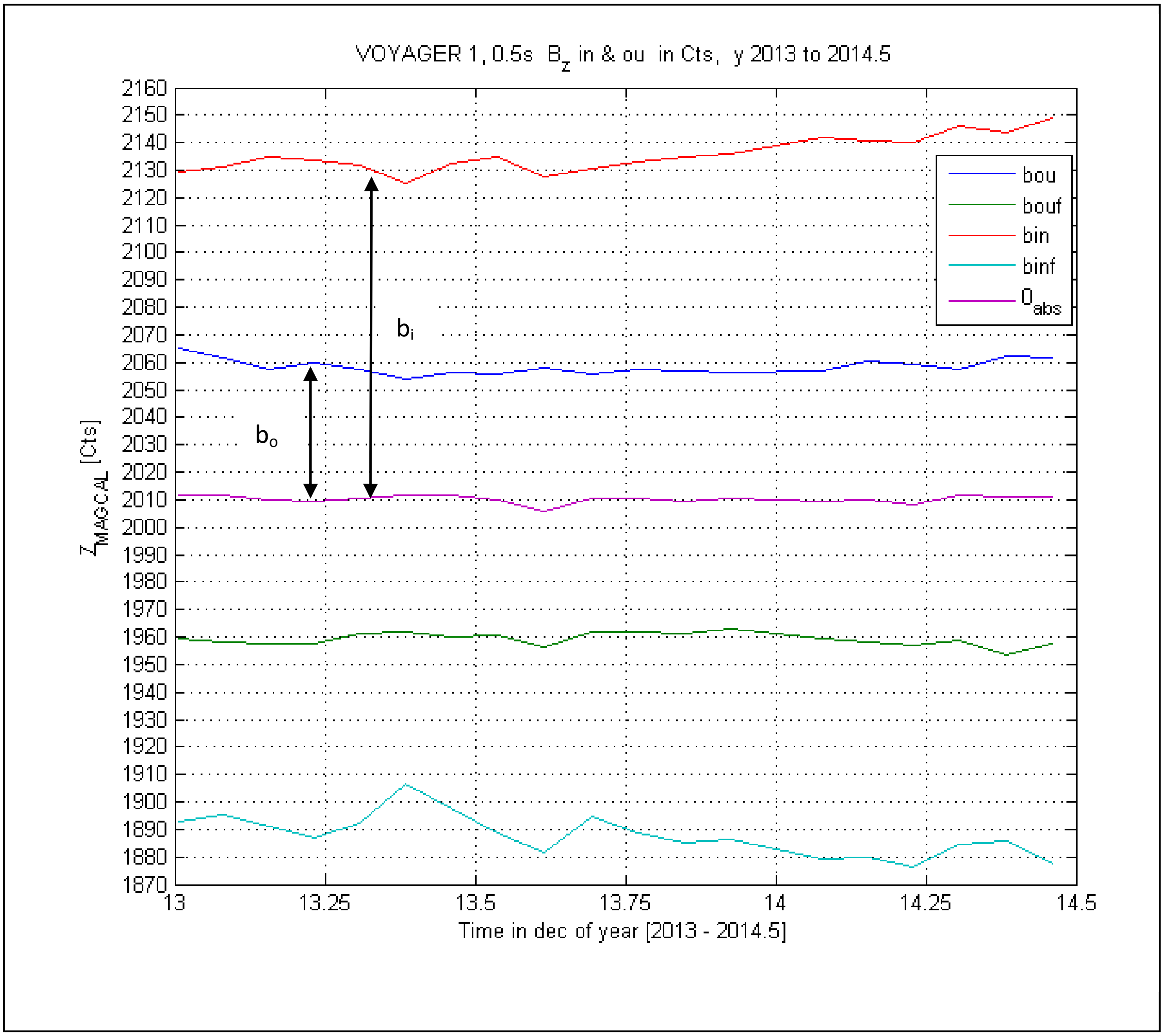
The same result is possible to obtain for the B_y component in the determination with the help of MAGROLs of the magnetized plasma medium B_y PL. This is not the case for the magnetized plasma medium B_z PL due to the fact that the MAGROL rotations are always around the Z_{PL}-axis.

5. Information gain on the plasma B: (i) from the reversal element of MAGCALs, and (ii) assumed constraints on |B|.

As it was pointed out before, in the case of the radial component from the Sun of the plasma magnetic field, i.e., B_{zPL} we are not helped by MAGROLs to determine the zero along this direction. However, the understanding of the average properties of the solar wind (SW) magnetic field and the identification of its departure from zero in the plasma sheath after crossing the SC the termination shock allow us to have a preliminary guess as to the possible value of this component of the magnetic field.

In addition, with the help of the quantities plotted (Figure 6) plus added constraints as we show below it is possible to achieve a reasonable estimate on the magnetic medium part of B_z PL,.

<u>Figure 6:</u> The purple-line is the absolute sensors zero along Z-PL (MAGCAL's zero). For details see text.



Here, we proceed as follows. Measured relative to the determined magnetic field zero [$0=(b_j+b_{jf})/2$] and identified in Cts for each sensor along direction j = X, Y, Z PL for inboard and outboard magnetometer we have the sensed magnetic field density signal, (see b_i and b_o marked with arrows on the left of Figure 6)

$b_i = b_{iSC} + b_m$, with i(=in board), iSC(=the SC B-field at in board sensor), m(=medium's B-field) and

$b_o = b_{oSC} + b_m$, with o(=out board).

As we see in Figure 4, with the help of MAGROLs the field of the medium explored with the instrument is known for direction X, and Y PL. This is not the case for the Z PL because completes the orthogonal coordinates system along the rotation axis.

In consequence, and at the current stage we estimate along Z PL the value of 'b_m' in the following way:

From the above two equations connecting the known observables b_i and b_o we define the unknown quantities

$b_{SC+} = (b_{iSC}+ b_{oSC})/2$

and

$b_{SC-} = (b_{iSC} - b_{oSC})/2$

In this way we get the relationship

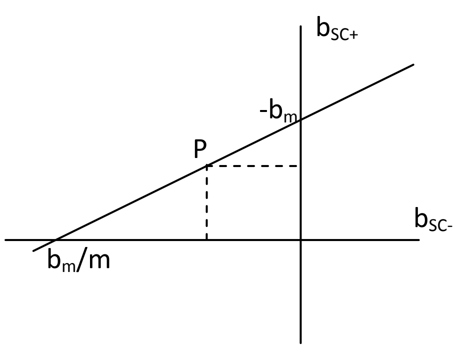
$b_{SC+} = m\, b_{SC-} - b_m$.

which is a linear equation with known slope

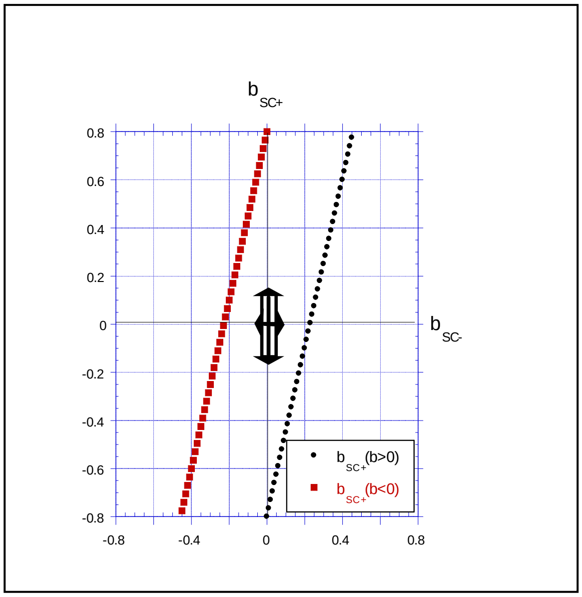
$m = (b_i + b_o)/(b_i - b_o)$

and the three unknowns b_{SC+}, b_{SC-}, and 'b_m.' Here the quantity of interest is 'b_m,' i.e., the magnetized field of the medium along Z PL. In the case like along X or Y PL 'b_m' is known and also so is the field of the SC at the out- and in-board magnetometers. In such case, in the space of the above defined 'coordinates' b_{SC-} and b_{SC+} a point 'P' is identified, as well as coordinate crossings with their values, see sketch in Figure 7a.

Figure 7a



<u>Figure 7b:</u> *Rectangular central-shape shows constraints on b_m*



In Figure 7a the line crosses the vertical at $b_{SC+}= -b_m$, and the horizontal at $b_{SC-}= b_m/m$. The value of m sets strongly hints at the possible value of unknown medium's 'b_m' along the B_{zPL} as well as an observed coherent deviation of the observed raw B_{zPL} in Figures 1, and for a non-raw B_{zPL} in Figure 2. There is also an observation that the intensity is small, particularly with respect to the current orientation of the assumed interstellar magnetic field observed by Voyager 1.

In consequence Figure 7b illustrates with the quoted oblong shape at its center the reasonable constraint range to be used for its value. The above is based on the knowledge we have of the observed value of b_{SC+}, b_{SC-} as observed along the other two directions X, and Y PL as well as the estimate made along Z PL of 'b_m' when it was noticed its departure from zero, illustrated in Figures 1 and 2 VOYAGER 1, in 2008, and for VOYAGER 2 in 2011.

Summing up we can say that with the use of MAGCALs technique for the direction of the component 'b_m' from Figures 1 and 2, as well as the relationships derived in this sections we obtain good constraints for the final estimate of the medium's 'B_{zPL}' with the dual magnetometer sensors along Z PL as it is observed as a function of time. Other refinements are possible in the determination of B_{zPL} (which may be used/needed in the future).

<u>Appendix</u>

<u>Example 1 of MAGCALs use with Voyager 1 B_{zPL}</u>. For the purpose of simplicity here we will consider the following. (i) A displacement of 20 Cts in VOY 1 B_{zPL} (bottom panel, Figure 1) from its zero value, assuming that neither steady trend to increase nor to decrease is recorded in MAGCALs as it appears to be the case in the Figure 6 shown interval for out-board MAGCALs. (*In addition we will simplify conditions assuming that conditions on MAGCALs stay put for the time interval that starts in year 2008, presented in Figure 1.)* Notice in Figure 6 a weak trend to increase intensity is observed in in-board MAGCALs. However, here we guide ourselves by principle 'B),' see Section 1. Hence, we make the assumption that this trend with B_{zPL} out-board is true, and from start we get in counts

$$B_{zPL} = 20 \text{ Ct}.$$

as our estimate. In this case with the information complete for the equation $b_{SC+}(b_{SC-})$, and from Figure 6, a value of m=(2140 – 2010)/(2060 – 2010) = 130/50 is obtained. In this case we obtain a

b_{SC-} ~ 80 Cts

and

b_{SC+} ~ 180 Cts

corresponding to an alternative solution

$b_m \sim m\, b_{SC-} - b_{SC+} = 130/50 \times 80$ Cts – 180 Cts

which gives an alternative value

b_m ~ 28 Cts

in this way we conclude that it is reasonable to say that an estimated value for B_{zPL} is given by

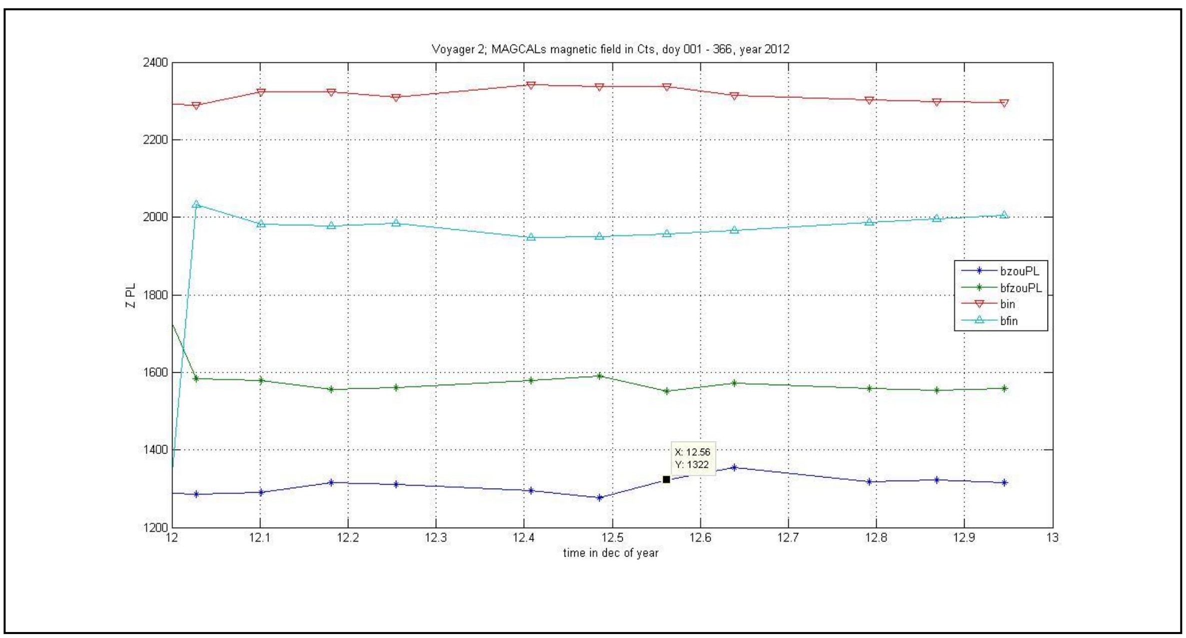
B_{zPL} = (28 + 20)/2 Cts +/- (28 – 20) Cts = 24 +/- 8 Cts.

For more confidence in our estimate it appears reasonable to round the estimate to

B_{zPL} = 20 +/- 10 Cts.

<u>Example 2</u> <u>of MAGCALs use with Voyager 2 B_{zPL}</u>. In this 2012 case, we observe that the slope ‘m<<1’ (see e.g., Figures 7). This case corresponds to the situation in which the magnitude of b_i and b_o are close in

<u>*Figure A1:*</u> Shown are in counts the values of Z PL. (*Not in plot in-(out-)board zero*-lines ‘0 = (b+bf)/2’!)



value but of opposite sign keeping m>0, i.e., the line has a near zero slope, positive as in Figures 7 in

$b_{SC+} = m\, b_{SC-} - b_m$

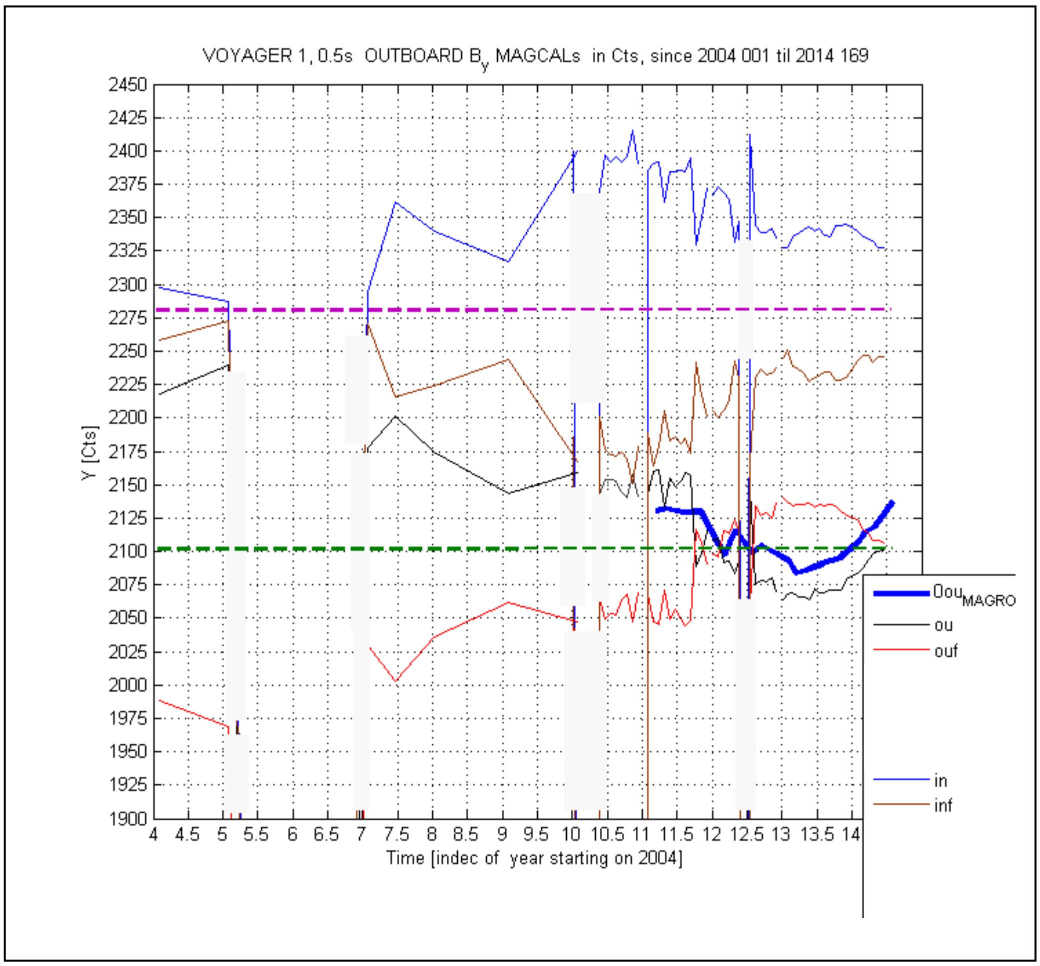
(equation from Section 5). Then by assuming that the small difference in magnitude between b_i and b_o (see Figure A1) is just due to the medium we set $b_{SC+} = 0\pm12$ Cts. For the equation above we get then the estimate

$$b_m = (b_i + b_o)/2 \cong m\ b_{SC-}$$

as the mediums component in the Z-direction. In the particular case of DOY 147, year 2012, this last relationship gives an estimated value for the medium $b_m = +12\pm12$ Cts along Z PL.

Finally we illustrate that the notion of an approximately constant value of the total component of the magnetic flux field $\mathbf{B}_{iT}$ (i = X, Y, Z in PL) is far of valid as shown by a long term evolution in time of the MAGCALs along the Y PL axis in Figure A2.

Figure A2. Thick-blue-line is the medium's zero, outboard sensor. Thin black and red lines are outboard MAGCAL's lines. Thin blue and brown lines are inboard MAGCALs lines. For details see text.



When the total component of **B** in one or all directions changes strongly, as seen in ***Figure A2***, a simple constraint on the value of the medium's (M) magnetic flux density component, to be identified by b_{im} and the magnetic flux density b_{iSC} to be the component contributed at the sensor by the SC, results from:

$$b_{im} + b_{iSC} = b_{iTotal}$$

then we can use the inequality

$$b_{im}^2 \leq b_{iTotal}^2 + b_{iSC}^2$$

henceforth

$$b_{im} < b_{iTotal}$$

is a weak constraint we can also use on the mediums magnetic field B_i PL ($i = X, Y, Z$). (Notice that this *weak* constraint will fail for the case → $|b_{im}| \cong |b_{iSC}|$ and $\mathrm{sign}(b_{im}) \neq \mathrm{sign}(b_{iSC})$!)

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